The low frequency spectrum of the CMB

- The CMB is a radiation which spectrum formed in an environment with high temperature and density, when matter and radiation were highly coupled.
- Under these conditions photons' distribution is Planckian

$$n(x) = \frac{1}{e^{x} - 1}$$

- In the primordial Universe energy density perturbations happened
- If they happened when red-shift $z > 10^7$ CMB keeps black body spectrum
- for $10^5 < z < 10^7$ thermalization is not enough efficient and the spectrum relaxes to a Bose-Einstein distribution

$$n(x) = \frac{1}{e^{x+\mu} - 1}$$

- After recombination the Universe becomes transparent to CMB which freely propagates

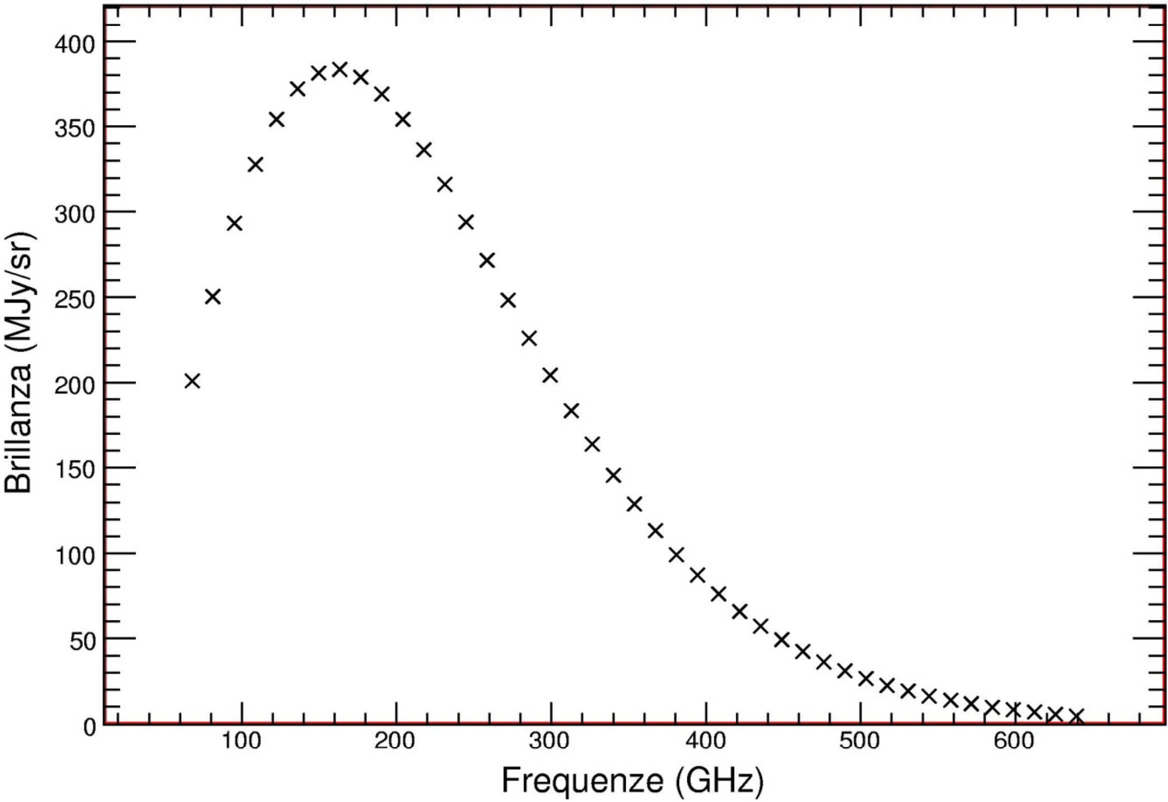
$$T(z) = T(z = 0) \cdot (1 + z)$$

FIRAS finds a
vondereful Black Body
pectrum in the
requency range

0-600 GHz

$T=2.725 \pm 0.001$ K

FIRAS can set only an
pper limit on the
hemical potential and
n the comptonization
arameter



$|\mu|<9 * 10^{-5}$ (C.L.95%)

$|y|<15 * 10^{-6}$ (C.L.95%)

How much distortion do we expect?

Frequency dip:

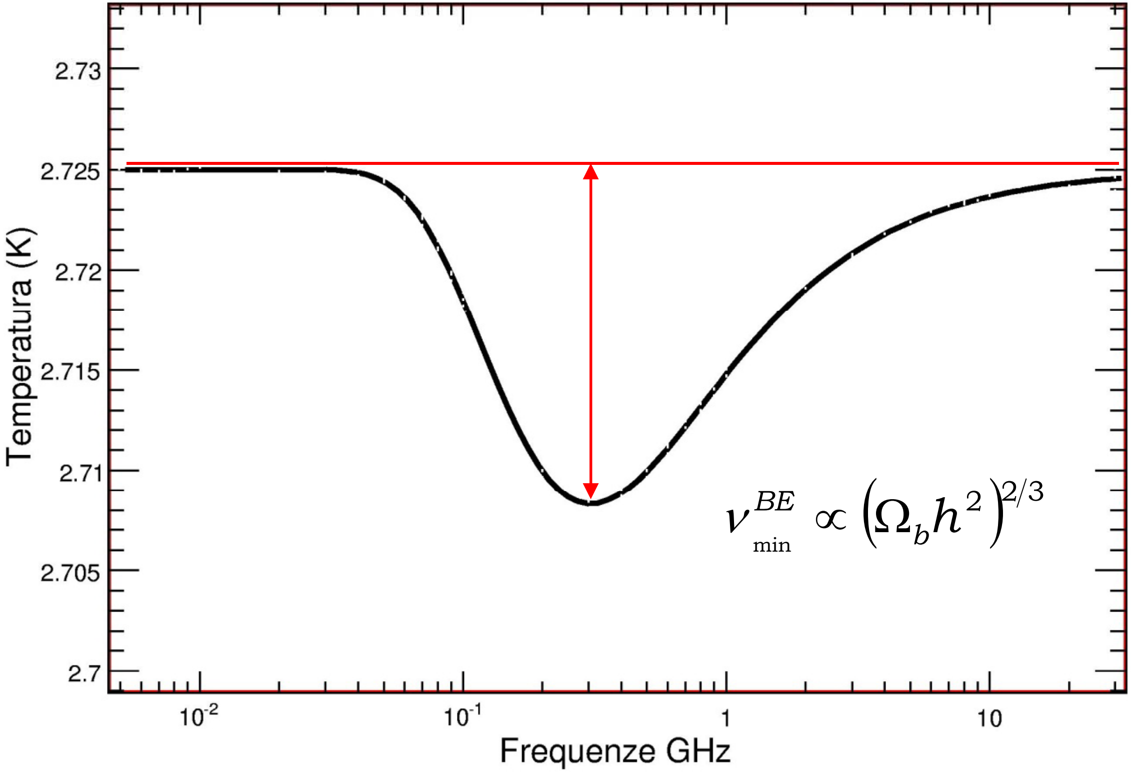
$\nu \approx 300$ MHz

Max distortion:

$\Delta T \approx 20$ mK

$\Omega_B h^2 = 0.0219 \pm 0.0007$

$h = 0.708 \pm 0.016$ WMAP 3y



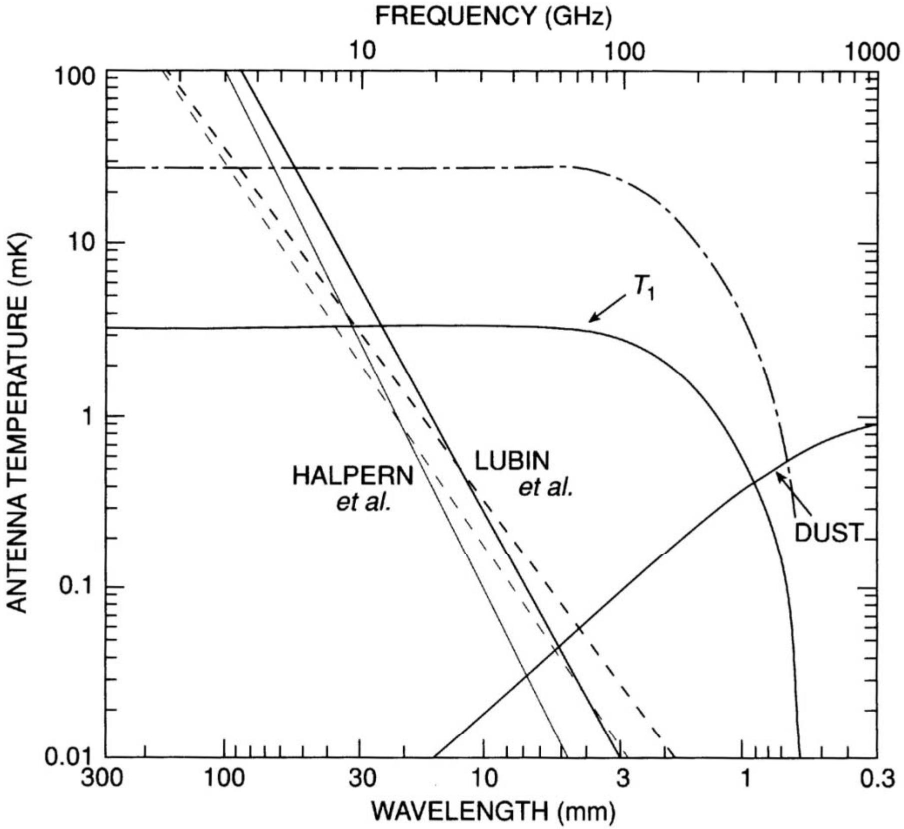
$$\nu_{\min}^{BE} \propto \left(\Omega_b h^2\right)^{2/3}$$

How much distortion do we expect?

- Temperature variation is small (ΔT/T = 0.7%)
- This kind of distortion is present only at low frequency

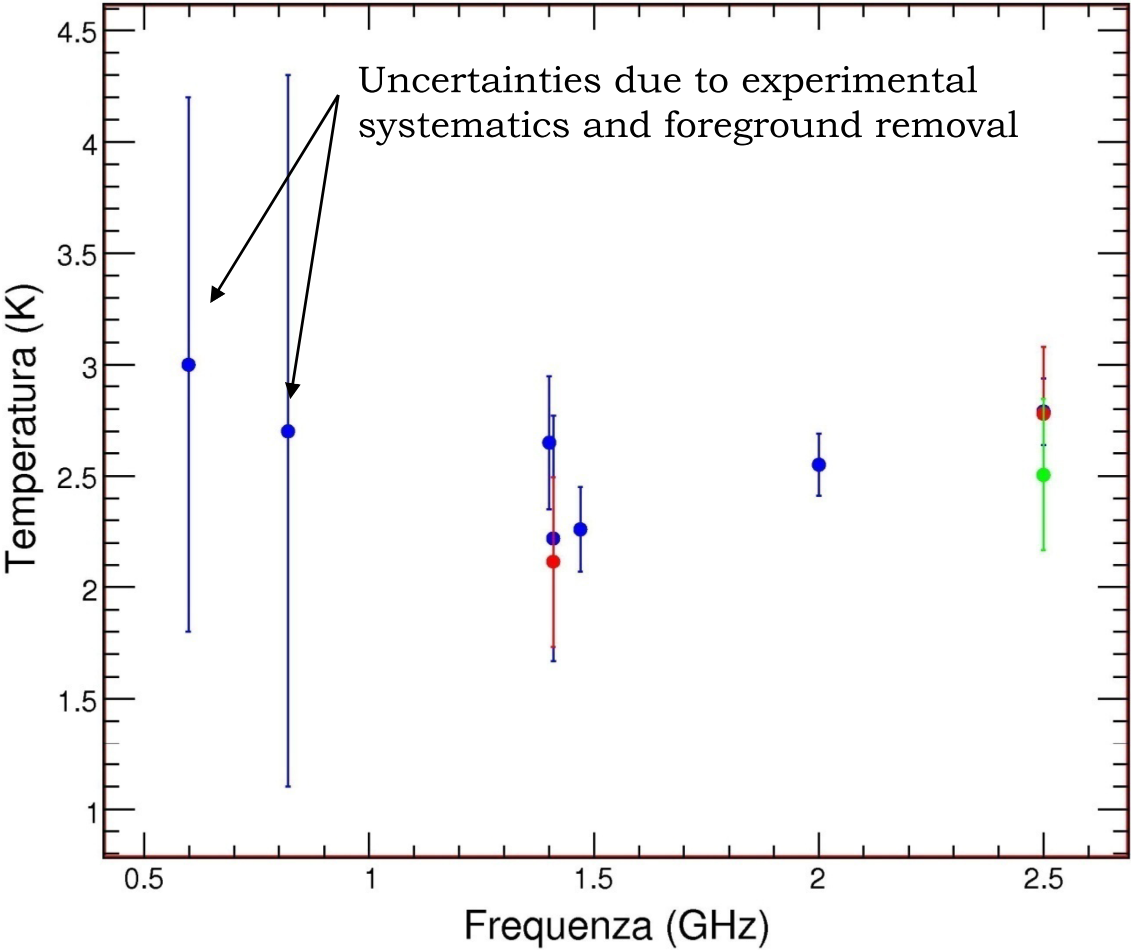
To derive the chemical potential low frequencies (ν < 3 GHz) must be investigated

But at these frequencies the Galactic (sinchrotron e bremsstrahlung), atmospheric and terrestrial (RFI) contaminations are very important



PARTRIDGE, 3K*: The cosmic microwave background radiation*

Experimental Status quo pre 2008



Uncertainties due to experimental systematics and foreground removal

TRIS Experiment

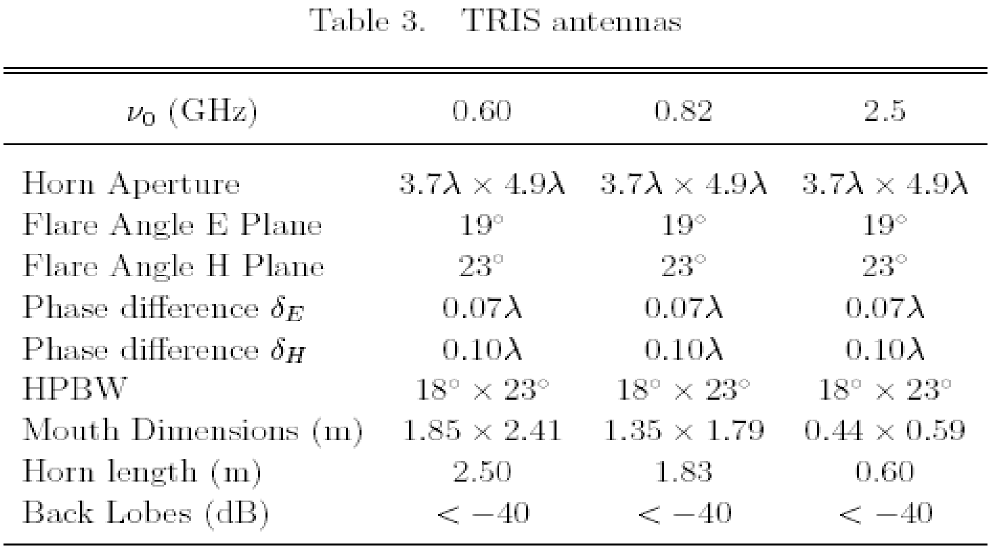


Table 3. TRIS antennas

ν_0 (GHz)	0.60	0.82	2.5
Horn Aperture	$3.7\lambda \times 4.9\lambda$	$3.7\lambda \times 4.9\lambda$	$3.7\lambda \times 4.9\lambda$
Flare Angle E Plane	19°	19°	19°
Flare Angle H Plane	23°	23°	23°
Phase difference δ_E	0.07λ	0.07λ	0.07λ
Phase difference δ_H	0.10λ	0.10λ	0.10λ
HPBW	$18^\circ \times 23^\circ$	$18^\circ \times 23^\circ$	$18^\circ \times 23^\circ$
Mouth Dimensions (m)	1.85×2.41	1.35×1.79	0.44×0.59
Horn length (m)	2.50	1.83	0.60
Back Lobes (dB)	< -40	< -40	< -40

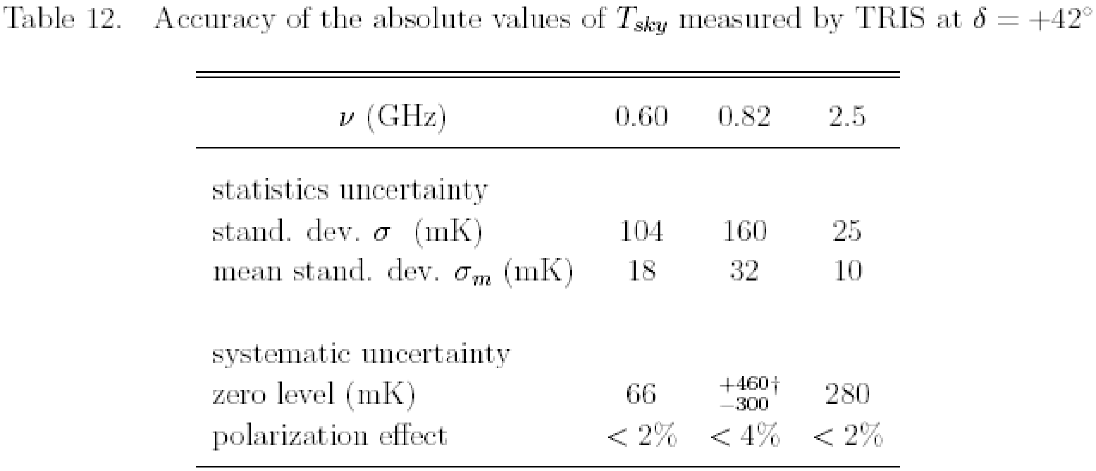
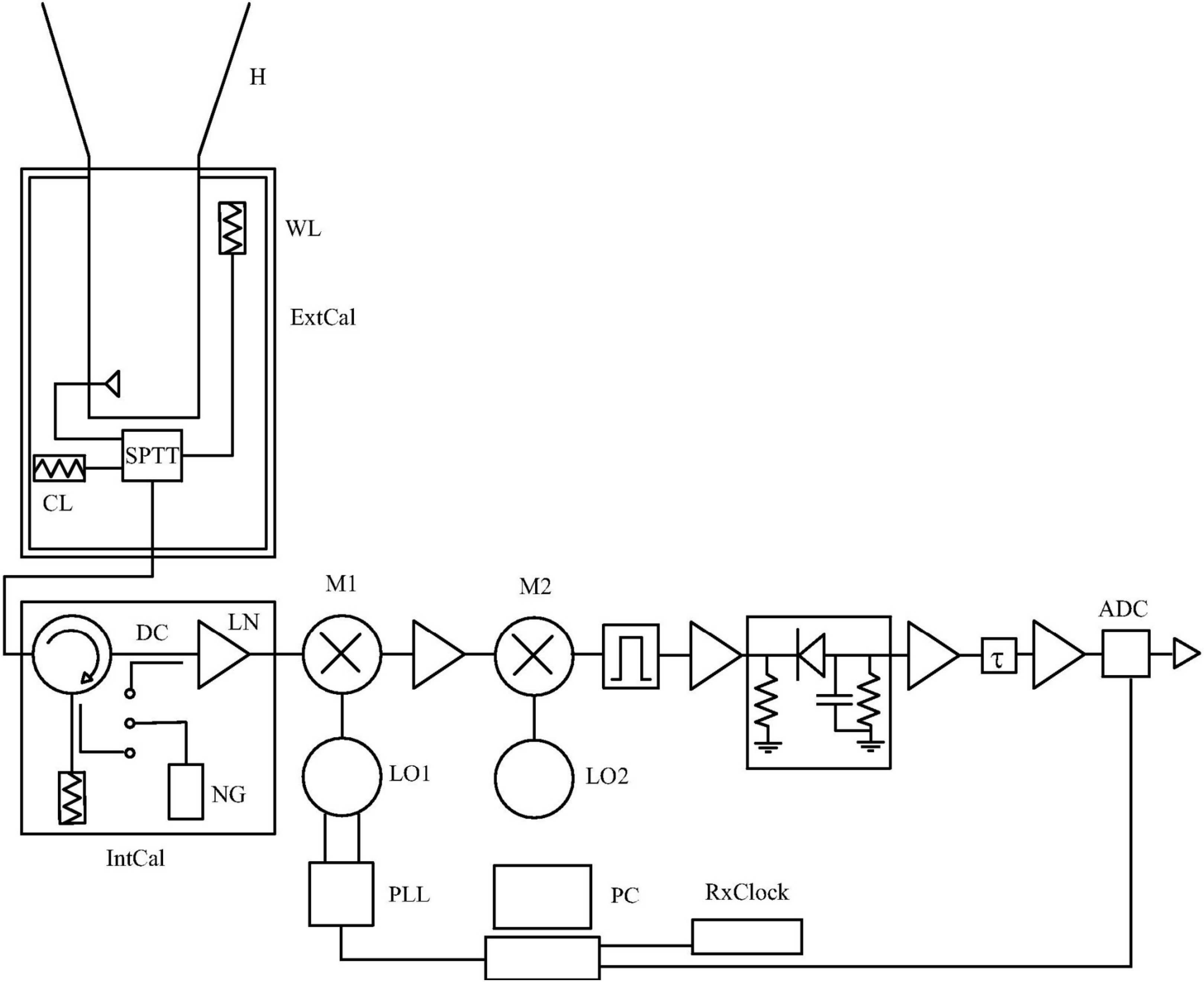


Table 12. Accuracy of the absolute values of T_{sky} measured by TRIS at $\delta = +42^\circ$

ν (GHz)	0.60	0.82	2.5
statistics uncertainty			
stand. dev. σ (mK)	104	160	25
mean stand. dev. σ_m (mK)	18	32	10
systematic uncertainty			
zero level (mK)	66	$^{+460\dagger}_{-300}$	280
polarization effect	$< 2\%$	$< 4\%$	$< 2\%$

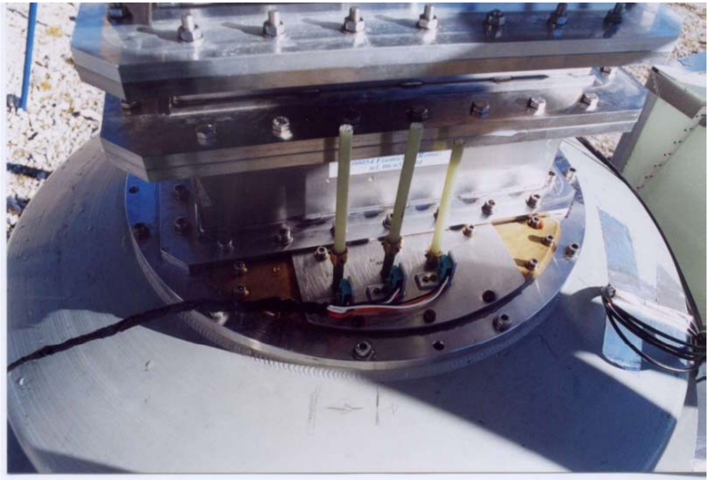

H
WL
ExtCal
SPTT
CL
DC
LN
M1
M2
ADC
τ
LO1
LO2
NG
IntCal
PLL
PC
RxClock

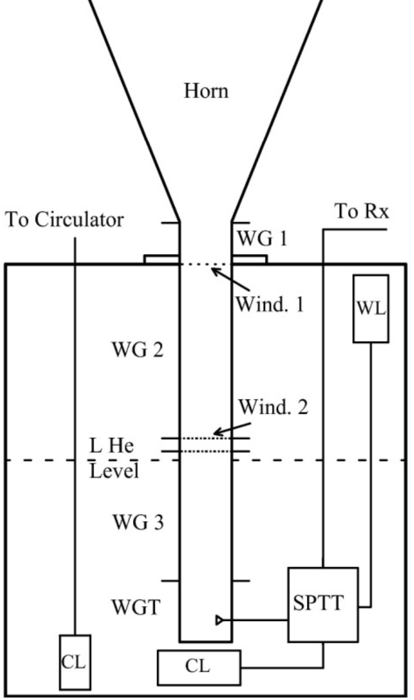
6 years to set-up plus one for absolute measurements

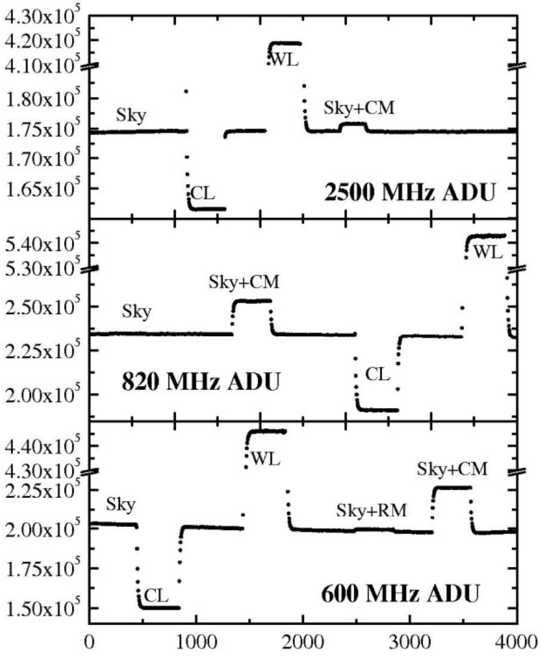
- We cooled critical components, replaced GaAs fet switches with pure passive ones, we measured all the measurable and modeled what is impossible to measure (only the horn flare) and…

…dressed everything
with the saint's patience…

Let's see how:







$$T_{sky}(\alpha,\delta,\nu) = T_{Gal}(\alpha,\delta,\nu) + T_{CMB}(\nu) + T_{UERS}(\nu)$$

$$T_{Gal}(\alpha,\delta,\nu) = K(\alpha,\delta)\cdot\nu^{-\beta(\alpha,\delta)}$$

$$T_{UERS}(\nu) = K_{UERS}\cdot\nu^{-\gamma_{UERS}}$$

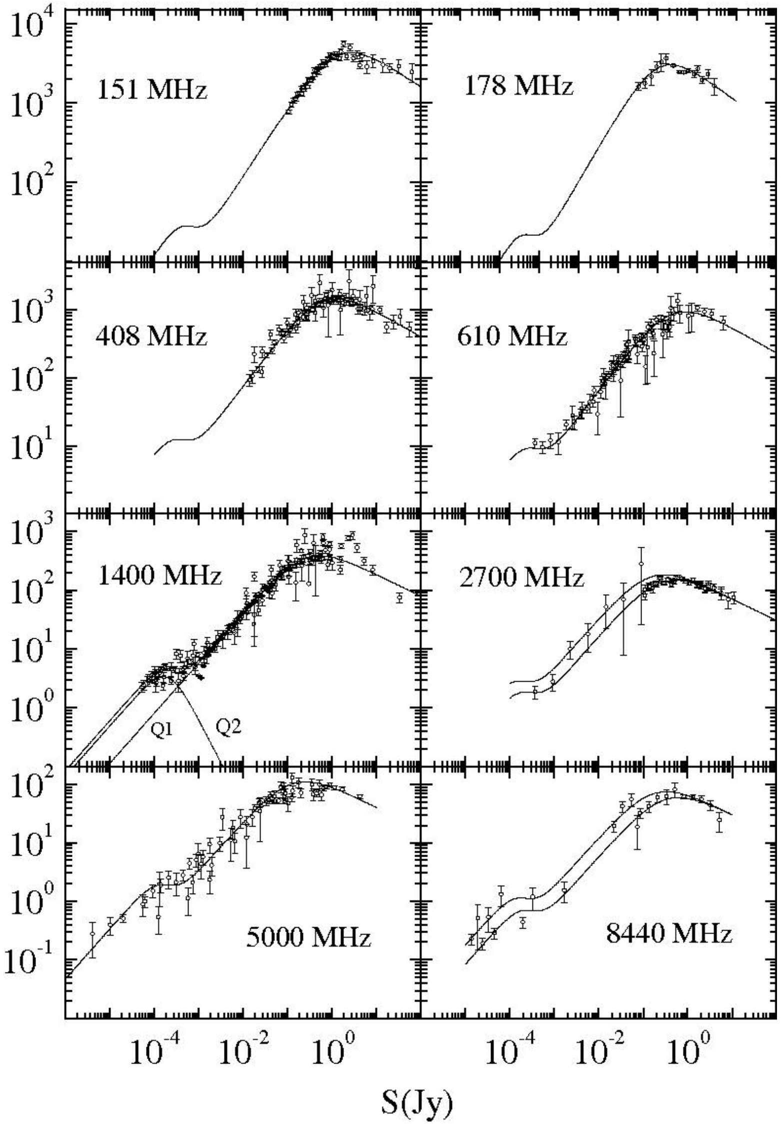
$$T_{sky} = \frac{T_a - T_{atm} - T_{env}}{1-\left(T_{atm}/T_{atm}^{0}\right)}$$

$$T_a = T_{cold}^{eff} + (S_{sky} - S_{cold})\cdot G$$

$$G = \frac{T_{warm}^{eff} - T_{cold}^{eff}}{S_{warm} - S_{cold}}$$

$$T_l^{eff} = \left[T_l^0 e^{-\tau_c} + \int_0^L T_c^0(x) e^{-\tau(x)}\left(\frac{d\tau}{dx}\right)dx\right]\left(1-r^2\right) + r^2 T_{RX}^{eff}$$

UERS problem: existing model were insufficiently accurate



$$Q(S) = Q_1(S) + Q_2(S) = \frac{1}{A_1 S^{\varepsilon_1} + B_1 S^{\beta_1}} + \frac{1}{A_2 S^{\varepsilon_2} + B_2 S^{\beta_2}}$$

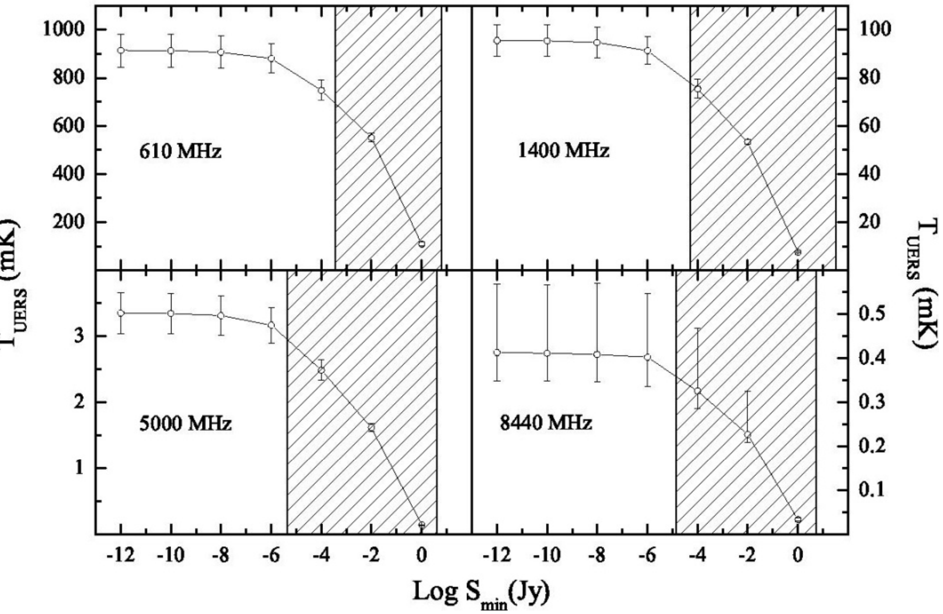
normalized to the Euclidean distribution of source

$$E(S) = S^{5/2}\left(\frac{dN}{dS}\right)$$

$$B_{uers}(\nu) = \int_{S_{\min}}^{S_{\max}} \frac{dN}{dS}(\nu)\, S\, dS$$

$$T_{uers}(\nu) = B_{uers}(\nu)\frac{\lambda^2}{2k_B}$$

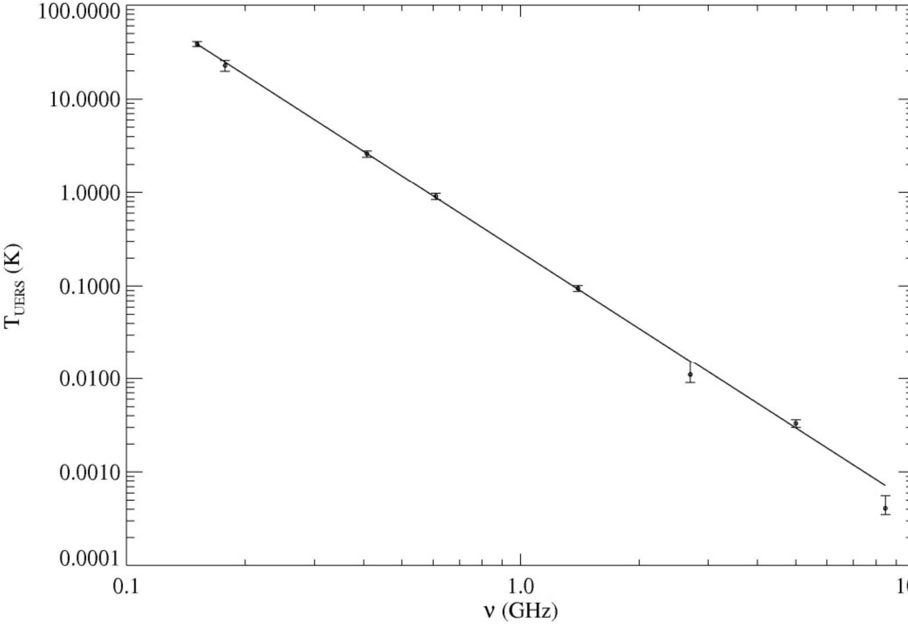
Can be integrated both for high and low fluxes



No problem at low fluxes

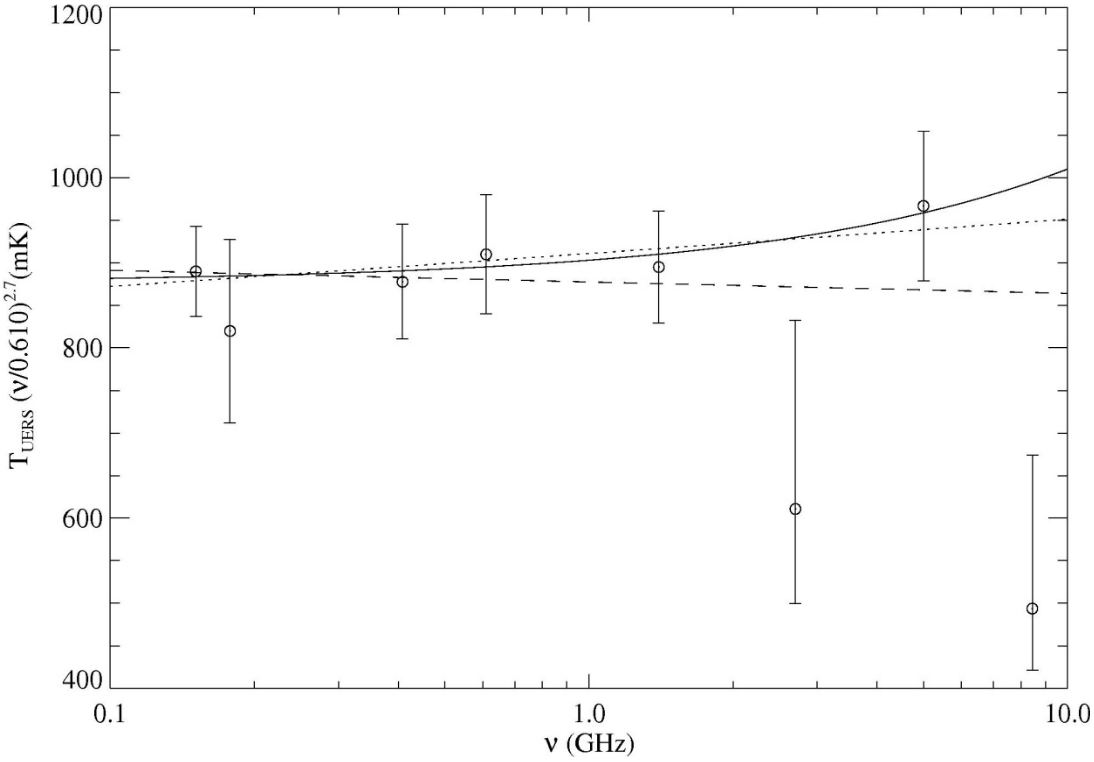
Uncertainties evaluated via MC

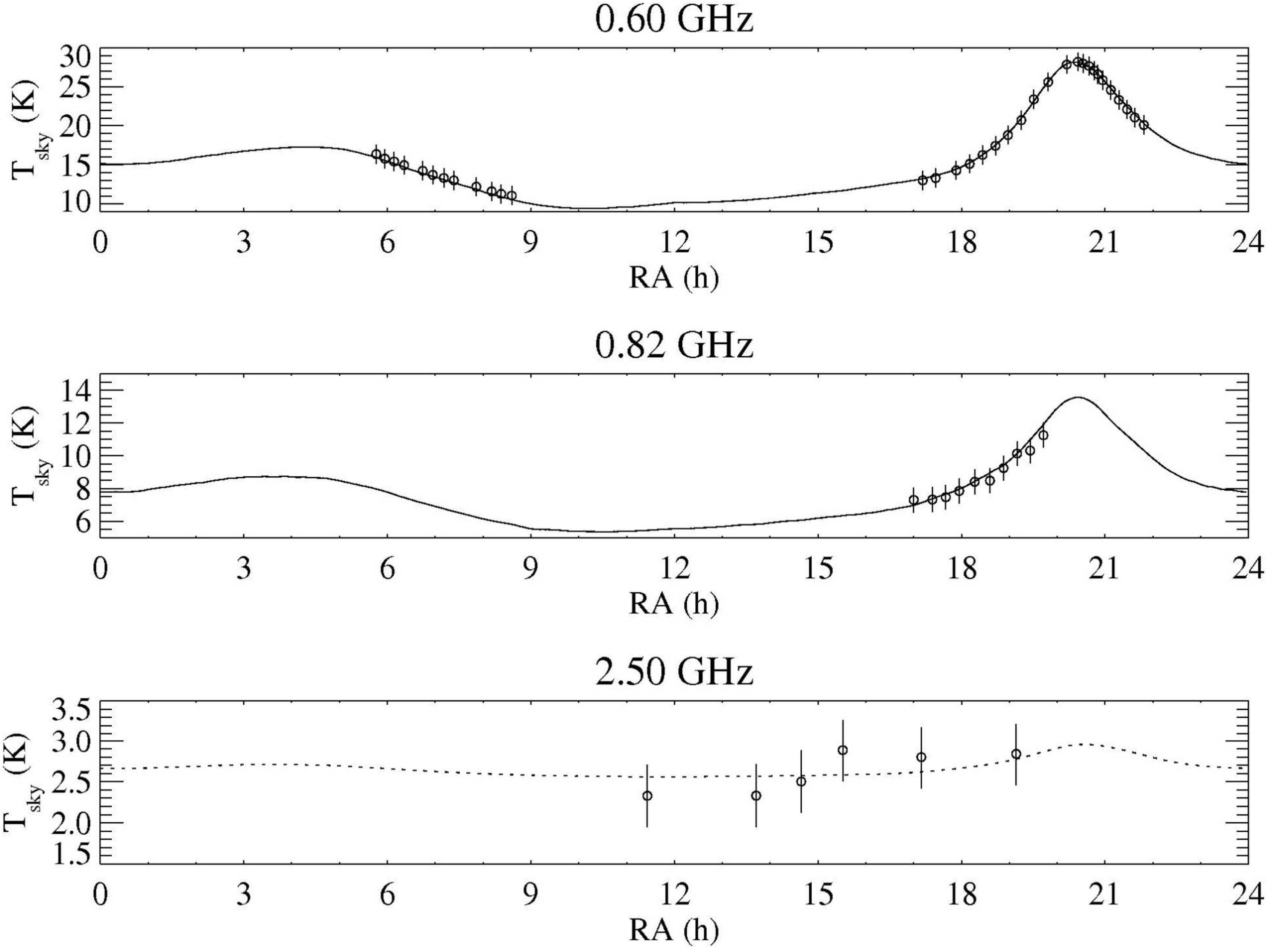
$$T_{uers}(\nu) = 880 \pm 30\left(\frac{\nu(MHz)}{610\ MHz}\right)^{-2.71\pm0.03} mK$$



Possible first detection of the 2 populations…

$$T_{uers}(\nu) = 876 \pm 22\left(\frac{\nu(MHz)}{610\ MHz}\right)^{-2.7} + 18.9 \pm 0.2\left(\frac{\nu(MHz)}{610\ MHz}\right)^{-2} mK$$




0.60 GHz
30
25
20
15
10
T_sky (K)
0
3
6
9
12
15
18
21
24
RA (h)
0.82 GHz
14
12
10
8
6
T_sky (K)
0
3
6
9
12
15
18
21
24
RA (h)
2.50 GHz
3.5
3.0
2.5
2.0
1.5
T_sky (K)
0
3
6
9
12
15
18
21
24
RA (h)

Position difference technique

$$
\begin{aligned}
T_{\rm sky}(\nu_1,\,\alpha_1) - T_{\rm UERS}(\nu_1) &= T_{\rm CMB}(\nu_1) + T_{\rm Gal}(\nu_1,\,\alpha_1),\\
T_{\rm sky}(\nu_1,\,\alpha_2) - T_{\rm UERS}(\nu_1) &= T_{\rm CMB}(\nu_1) + T_{\rm Gal}(\nu_1,\,\alpha_2),\\
T_{\rm sky}(\nu_2,\,\alpha_1) - T_{\rm UERS}(\nu_2) &= T_{\rm CMB}(\nu_2) + T_{\rm Gal}(\nu_2,\,\alpha_1),\\
T_{\rm sky}(\nu_2,\,\alpha_2) - T_{\rm UERS}(\nu_2) &= T_{\rm CMB}(\nu_2) + T_{\rm Gal}(\nu_2,\,\alpha_2).
\end{aligned}
$$

$$T_{\rm Gal}(\nu,\,\alpha) = T_{\rm Gal}(\nu_0,\,\alpha)\left(\frac{\nu}{\nu_0}\right)^{\beta(\alpha,\,\nu,\,\nu_0)}$$

$$
\begin{aligned}
T_{\rm sky}(\nu_1,\,\alpha_1) - T_{\rm sky}(\nu_1,\,\alpha_2) &= T_{\rm Gal}(\nu_1,\,\alpha_1) - T_{\rm Gal}(\nu_1,\,\alpha_2),\\
T_{\rm sky}(\nu_2,\,\alpha_1) - T_{\rm sky}(\nu_2,\,\alpha_2) &= T_{\rm Gal}(\nu_1,\,\alpha_1)m(\alpha_1)\\
&\quad - T_{\rm Gal}(\nu_1,\,\alpha_2)m(\alpha_2),
\end{aligned}
$$

$$m(\alpha) = (\nu_2/\nu_1)^{\beta(\alpha)}$$

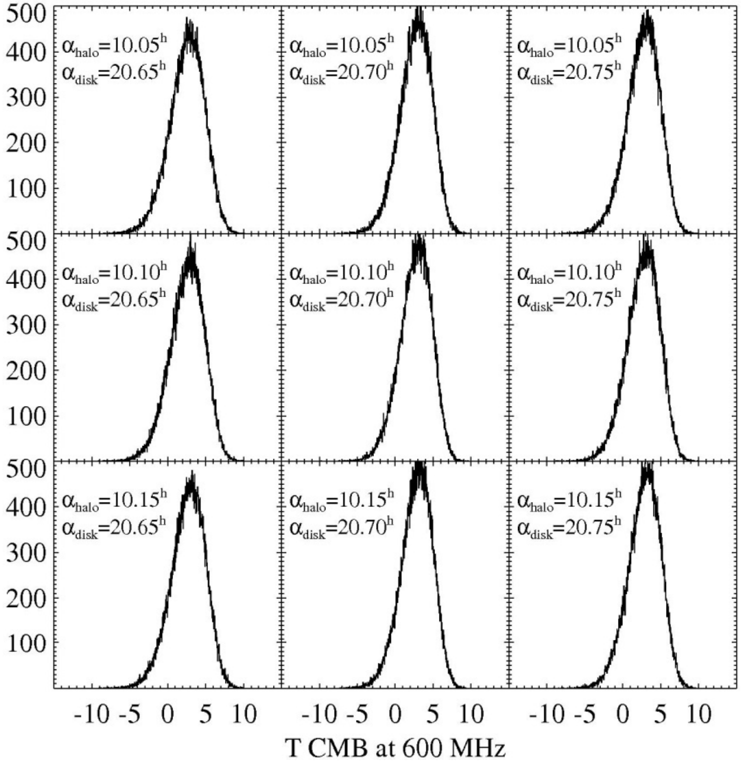
with $m(\alpha) = (\nu_2/\nu_1)^{\beta(\alpha)}$. We can use these equations to separate the microwave sky components if we can find two positions α_1 and α_2 such that $\beta(\alpha_1) \neq \beta(\alpha_2)$ $[m(\alpha_1) \neq m(\alpha_2)]$, $T_{\rm sky}(\nu_1,\,\alpha_1) \neq T_{\rm sky}(\nu_1,\,\alpha_2)$, and $T_{\rm sky}(\nu_2,\,\alpha_1) \neq T_{\rm sky}(\nu_2,\,\alpha_2)$. When these conditions, necessary to break the degeneracy, are satisfied, from equation (4) follows

$$
\begin{aligned}
&\left[T_{\rm sky}(\nu_2,\,\alpha_1) - T_{\rm sky}(\nu_2,\,\alpha_2)\right]\\
&-\left[T_{\rm sky}(\nu_1,\,\alpha_1) - T_{\rm sky}(\nu_1,\,\alpha_2)\right]m(\alpha_1)\\
&\qquad = T_{\rm Gal}(\nu_1,\,\alpha_2)[m(\alpha_1) - m(\alpha_2)],
\end{aligned}
$$

Important prior from TRIS high quality drift scan data

an equation we can use to extract $T_{\rm Gal}$, if $m(\alpha_1)$ and $m(\alpha_2)$ are known. If m is unknown, we can look for different pairs of points close to α_1 and α_2, respectively, write a system of equations, and extract $T_{\rm Gal}(\alpha)$ and $m(\alpha)$. Finally, going back to equation (2), we can get a number of values of $T_{\rm CMB}(\nu)$ in the sky regions around α_1 and α_2.

- We also performed MC analysis to derive all the parameters simultaneously and to get the overall error budget on the CMB temperature



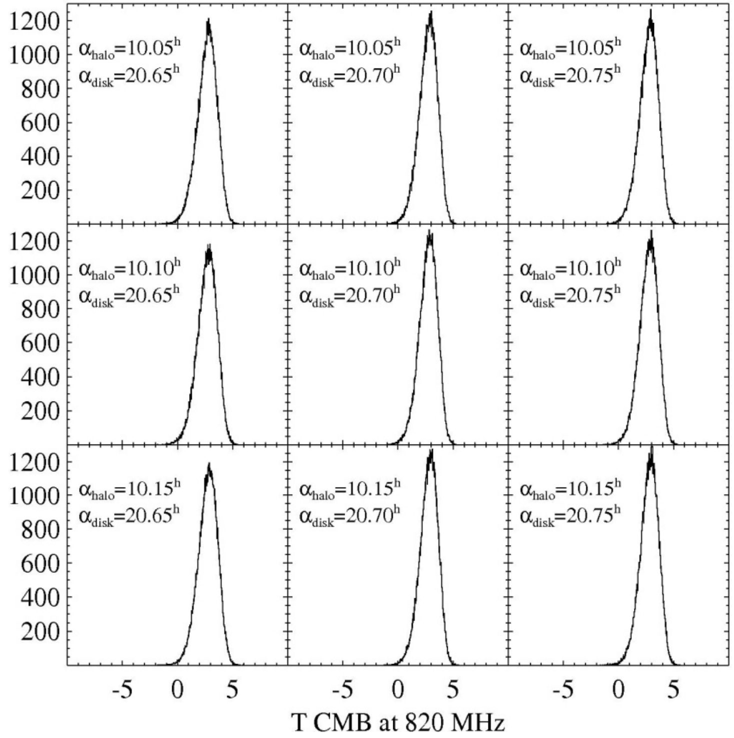


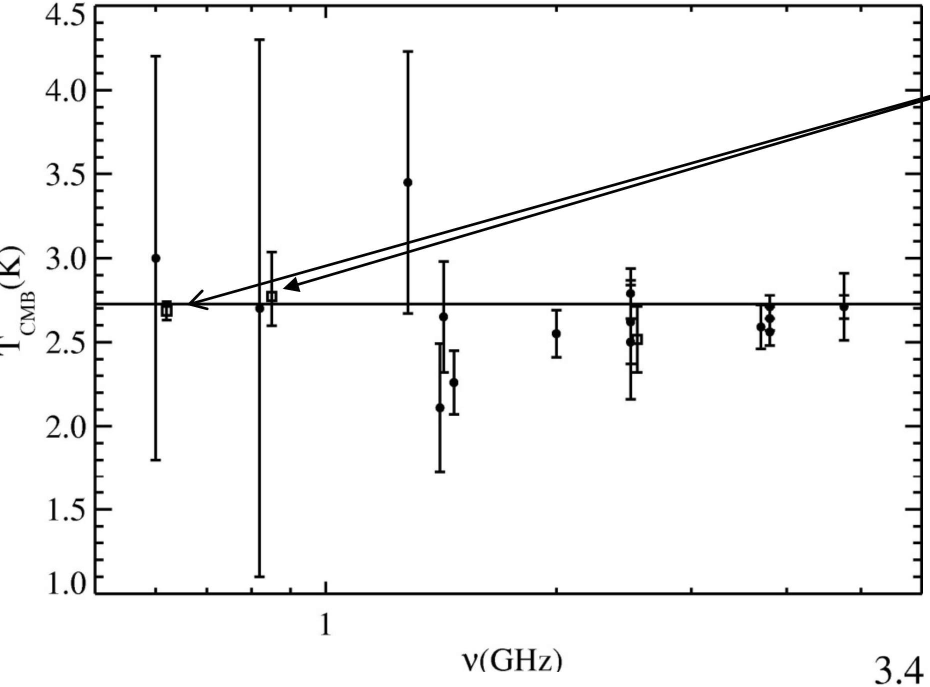
TABLE 14

TRIS RESULTS SUMMARY

Parameter	$\alpha^1 = 10^{\rm h}00^{\rm m}$	$\alpha^2 = 20^{\rm h}24^{\rm m}$
$\nu = 0.6$ GHz		
$T_{\rm sky}$ (K)............................	9.390 ± 0.066 (syst) $\pm$ 0.018 (stat)	28.190 ± 0.066 (syst) $\pm$ 0.018 (stat)
$T_{\rm Gal}$ (K)............................	5.72 ± 0.07	24.44 ± 0.07
$T_{\rm UERS}$ (K)........................	0.934 ± 0.024	0.934 ± 0.024
$T_{\rm CMB}$ (K).........................	2.823 ± 0.066 (syst) $\pm$ 0.129 (MC)[a]	2.823 ± 0.066 (syst) $\pm$ 0.129 (MC)[a]
$T^{\rm th}_{\rm CMB}$ (K).........................	2.837 ± 0.066 (syst) $\pm$ 0.129 (MC)[a]	2.837 ± 0.066 (syst) $\pm$ 0.129 (MC)[a]
$\nu = 0.82$ GHz		
$T_{\rm sky}$ (K)............................	$5.37^{+0.46}_{-0.30}$ (syst) $\pm$ 0.03 (stat)	$13.57^{+0.46}_{-0.30}$ (syst) $\pm$ 0.03 (stat)
$T_{\rm Gal}$ (K)............................	2.21 ± 0.03	10.38 ± 0.03
$T_{\rm UERS}$ (K)........................	0.408 ± 0.010	0.408 ± 0.010
$T_{\rm CMB}$ (K).........................	$2.783^{+0.430}_{-0.300}$ (syst) $\pm$ 0.051 (MC)[a]	$2.783^{+0.430}_{-0.300}$ (syst) $\pm$ 0.051 (MC)[a]
$T^{\rm th}_{\rm CMB}$ (K).........................	$2.803^{+0.430}_{-0.300}$ (syst) $\pm$ 0.051 (MC)[a]	$2.803^{+0.430}_{-0.300}$ (syst) $\pm$ 0.051 (MC)[a]
$\nu = 2.5$ GHz		
$T_{\rm sky}$ (K)............................	2.57 ± 0.28 (syst) $\pm$ 0.10 (stat)	2.99 ± 0.28 (syst) $\pm$ 0.10 (stat)
$T_{\rm Gal}$[b] (K).........................	0.091 ± 0.093 (syst) $\pm$ 0.005 (stat)	0.471 ± 0.093 (syst) $\pm$ 0.027 (stat)
$T_{\rm UERS}$ (K)........................	0.022 ± 0.001	0.022 ± 0.001
$T_{\rm CMB}$ (K).........................	2.458 ± 0.284 (syst) $\pm$ 0.139 (stat)	2.458 ± 0.284 (syst) $\pm$ 0.139 (stat)
$T^{\rm th}_{\rm CMB}$ (K).........................	2.516 ± 0.284 (syst) $\pm$ 0.139 (stat)	2.516 ± 0.284 (syst) $\pm$ 0.139 (stat)

[a] This uncertainty was evaluated by means of Monte Carlo simulations, as described in Paper II.

[b] Due to the incompleteness of the TRIS drift scan at 2.5 GHz, here $T_{\rm Gal}$ is extrapolated by the Reich & Reich (1986) map at 1.42 GHz convolved with the TRIS beam and using the local spectral index calculated from our data at 0.6 and 0.82 GHz. The quoted systematic uncertainty for $T_{\rm Gal}$ is relative to the determination of the Galactic signal at 1.42 GHz, starting from the absolute measurements at 0.6 and 0.82 GHz.



New data slightly shifted to be visible

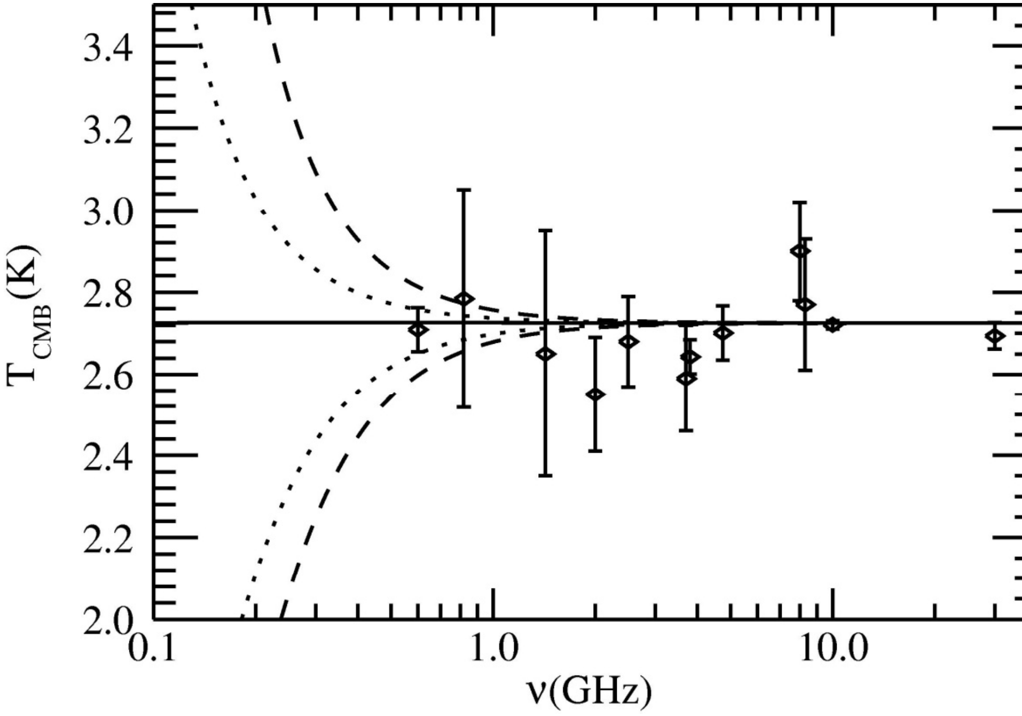
Results obtained by fitting the chemical potential and Yff parameters simultaneously

$-6.3 \times 10^{-6} < Y_{ff} < 12.6 \times 10^{-6}$ at 95% CL

$|\mu| < 6 \times 10^{-5}$ at 95% CL

$$\Delta T_{ff} = T_0 \frac{Y_{ff}}{x^2}$$

This kind of distortion is expected in the case of reionization of the intergalactic medium (IGM). The amplitude of the cosmological signal depends on the integrated column density of ionized gas produced at the redshift of formation of the first collapsed objects and on the thermal history of the IGM through the electrons' temperature



Still Alive?

Milano Cold Network

S parameters measurement from 50 MHz to 110 GHz (50-75 GHz lacking)

down to 4 K (1 W @ 4K) with calibration standards at 4 K

2 2-ports or 1 4-ports device characterization

Totally oil free

8+8 (+8+8+….) calibrated thermometers

Can be remotely operated and data acquired

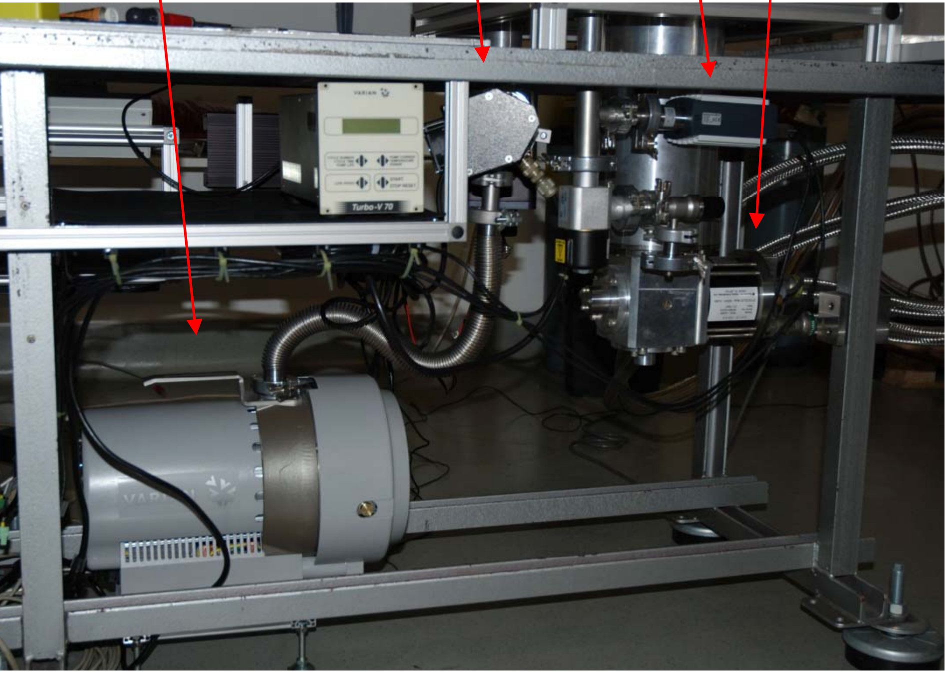
Ready to measure in about 6 hours

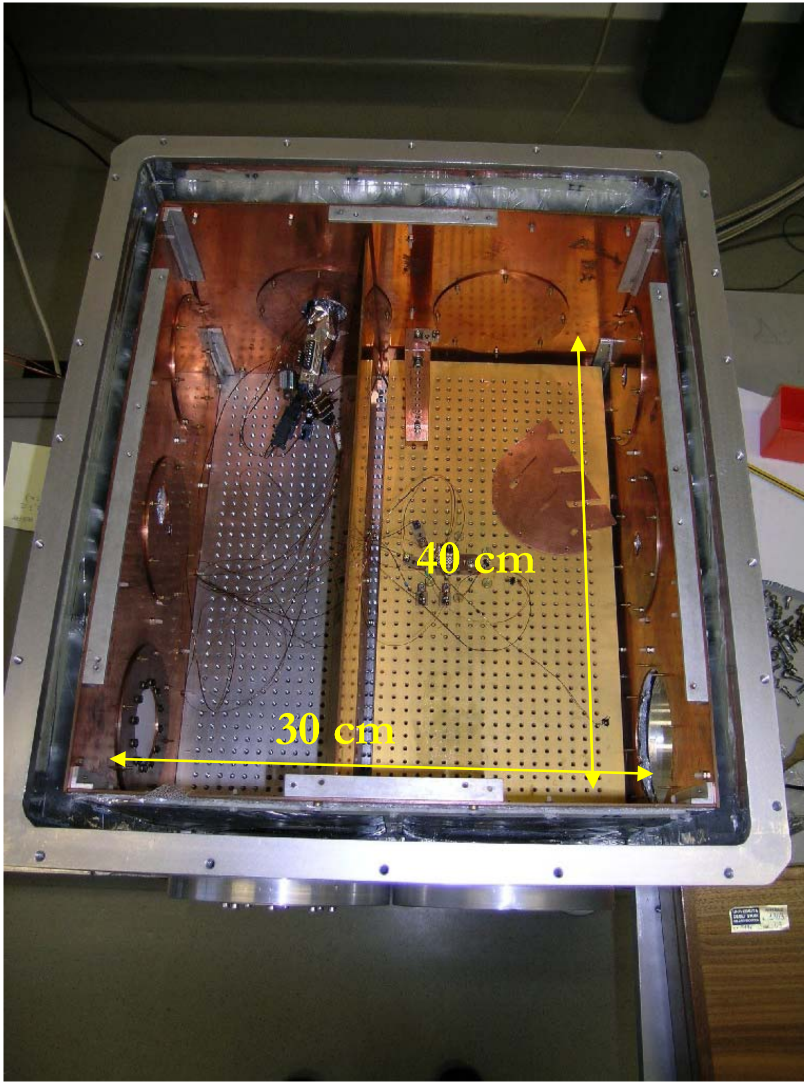
Sumitomo cold head

Leybold 13 decades pressure gauge

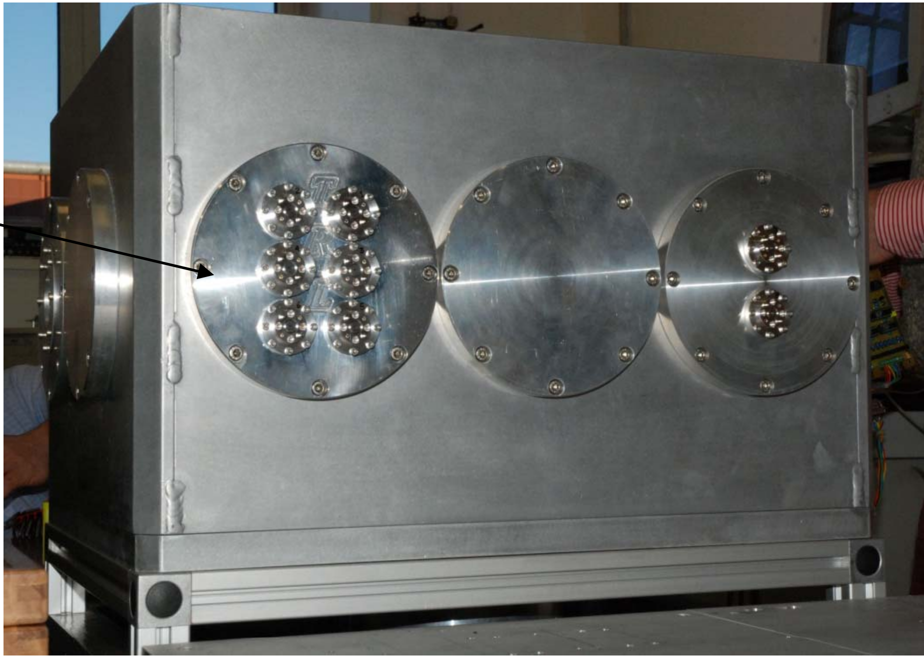
Turbo pump

Scroll pump

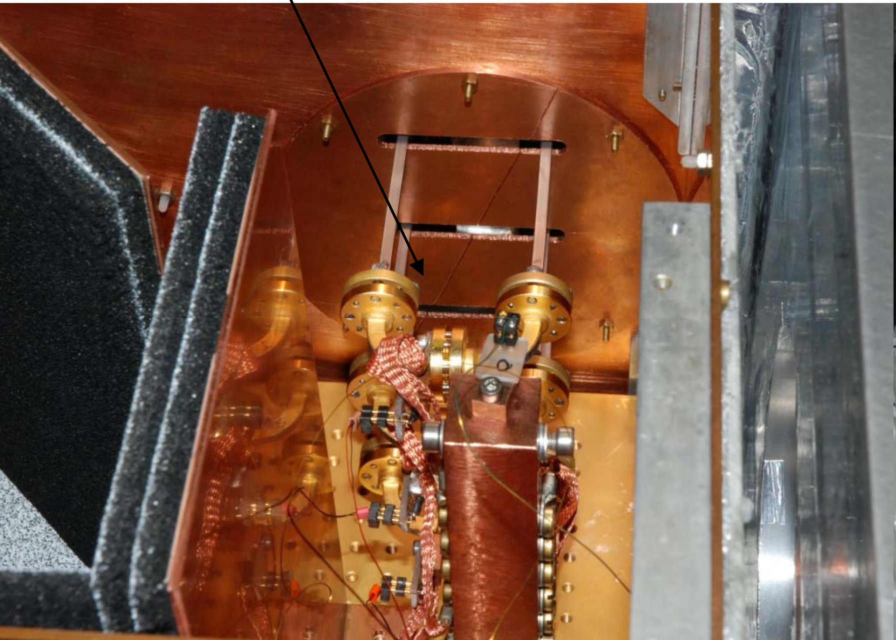


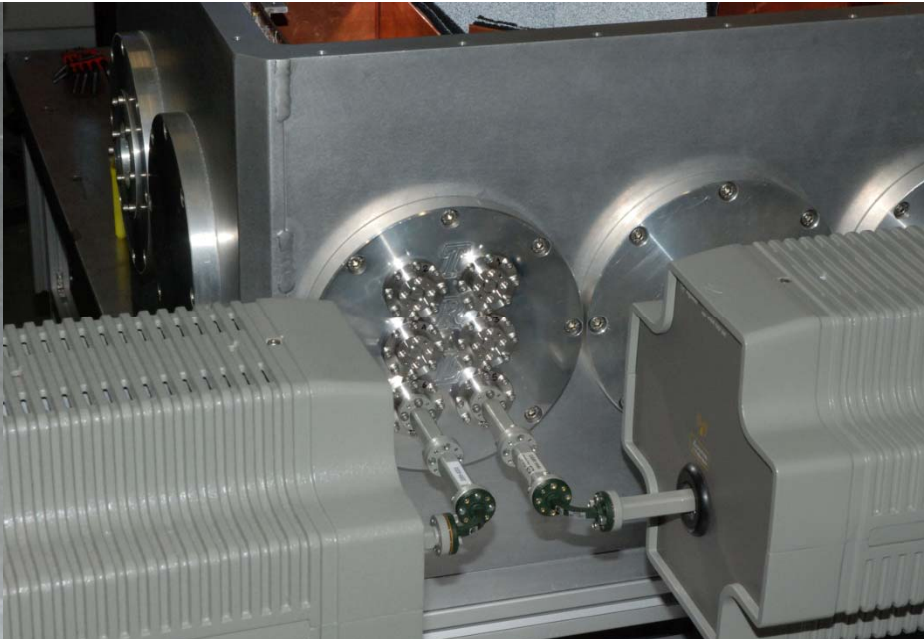


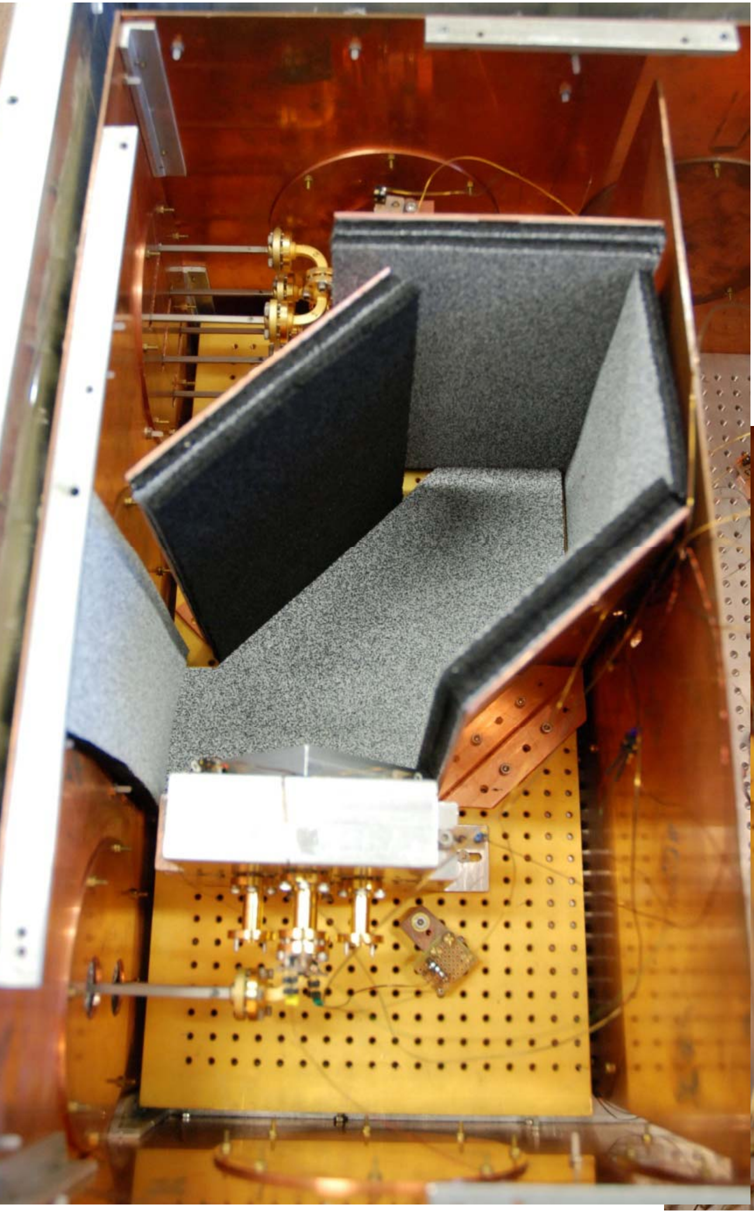
TRL calibration ports



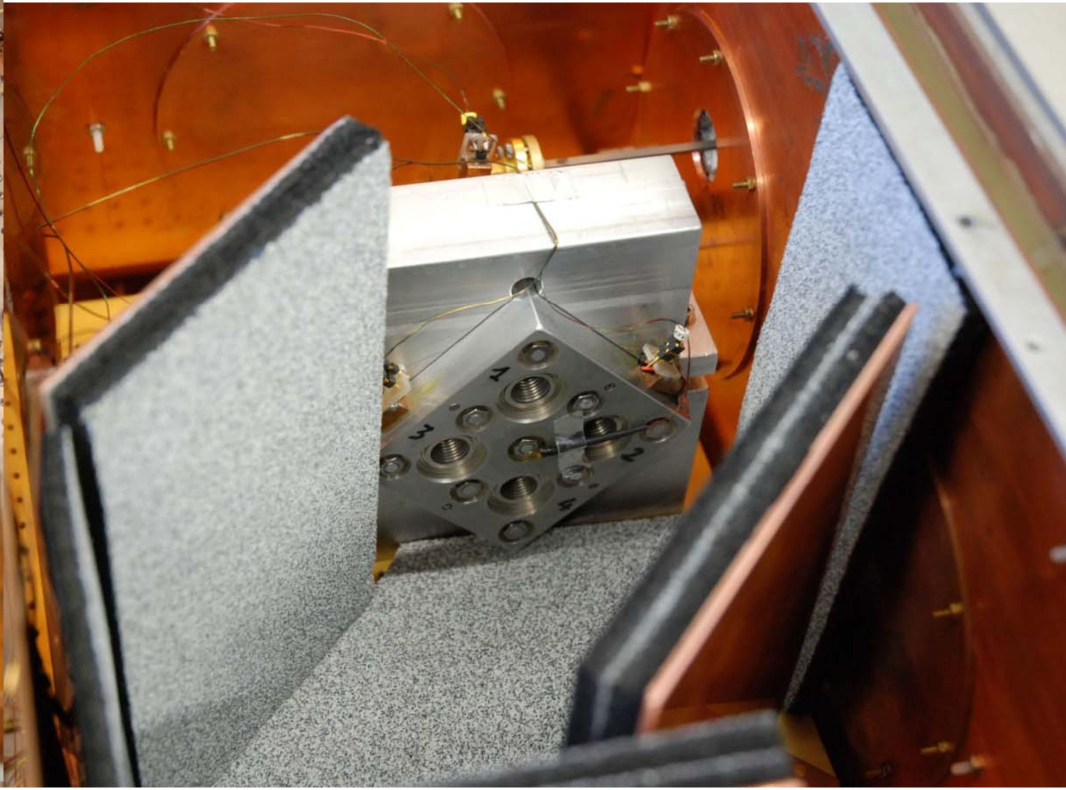
TRL standards

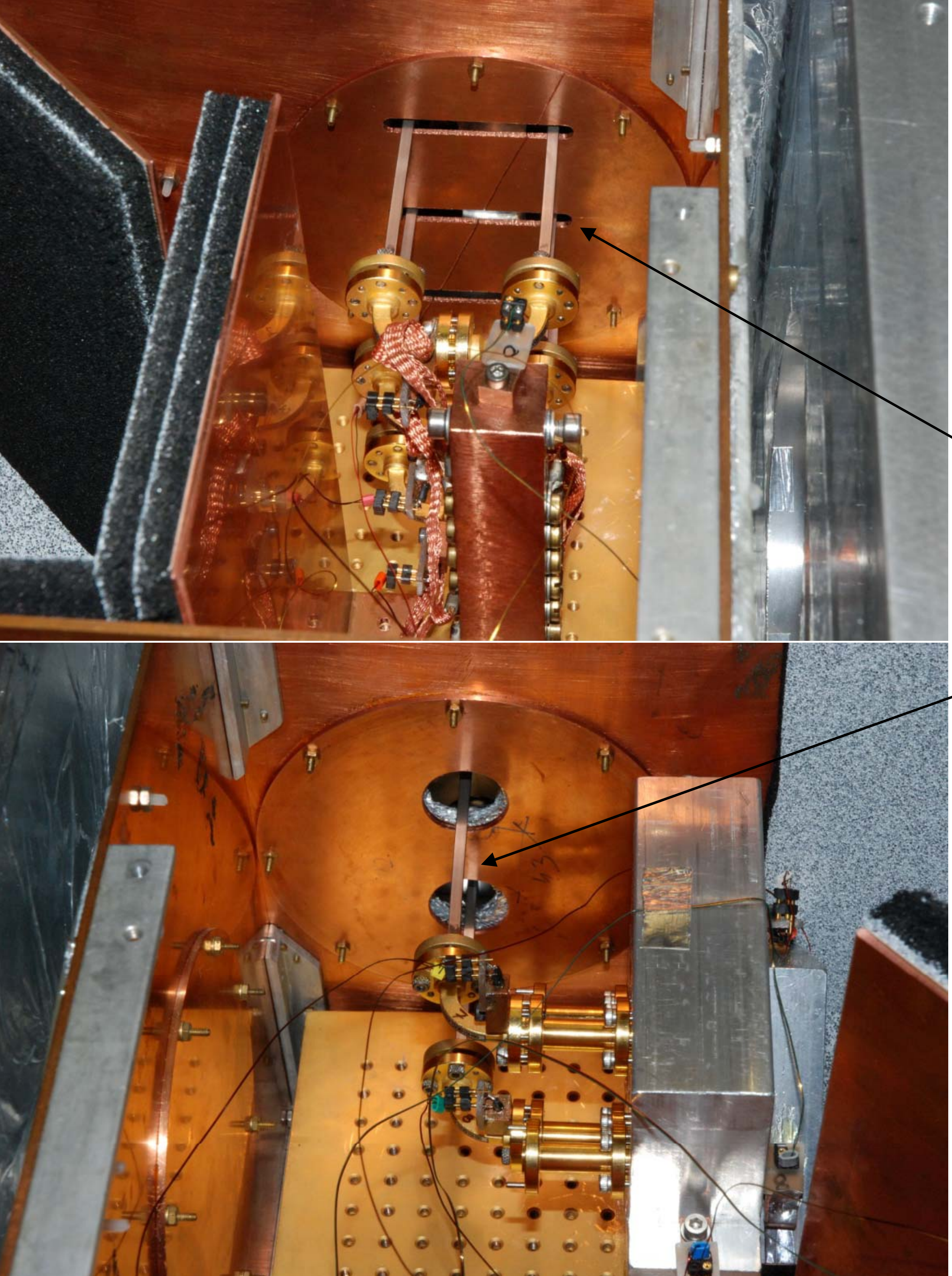






Example:
S11 measurements of a
100 GHz feed array prototype





Same line
same thermal profile
for both calibration
standards and DUT